

Infrared imaging as a means of visually characterizing the thermoacoustic onset process influenced by a Helmholtz resonator[☆]

Bo Wang^a, Limin Qiu^{a,*}, Kai Wang^a, Daming Sun^a, Xuejun Zhang^a, Weijuan Yang^b, Junhu Zhou^b

^a Institute of Refrigeration and Cryogenics, Zhejiang University, Hangzhou 310027, PR China

^b State Key Laboratory of Clean Energy Utilization, Zhejiang University, Hangzhou 310027, PR China

ARTICLE INFO

Article history:

Received 28 November 2010

Received in revised form 13 August 2011

Accepted 7 December 2011

Available online 31 December 2011

Keywords:

Thermoacoustic engine

Onset

Infrared imaging

Regenerator

Temperature distribution

ABSTRACT

A Helmholtz resonator can be used as a transmission part to connect the thermoacoustic engine (TE) with its load. However, the resonator can significantly influence the performance of the TE. In order to investigate the impact of a Helmholtz resonator on the onset process of a TE, infrared (IR) imaging is firstly used as a visualization method to characterize the onset mechanism. The influence of dimensions of the Helmholtz resonator on the onset process are analyzed experimentally and theoretically. Results show that the Helmholtz resonator reduces the pressure amplitude at the onset moment and increases the onset temperature of the TE, both of which depend on the acoustic power absorbed from the TE. Onset without a sudden increase of pressure amplitude is observed with the Helmholtz resonator at resonance length. This paper shows that IR imaging is an effective way to characterize the temperature distribution in a TE study.

© 2011 Elsevier Ltd. All rights reserved.

1. Introduction

A thermoacoustic engine (TE) with no moving parts is a new type of long-life, non-polluting engine that can utilize thermal energy, even low grade thermal energy [1]. It can be used to drive coolers and generators in the fields of electronic device cooling, natural gas liquefaction, pulse tube refrigeration, and power generation. Good performance of these cooling and power generation systems requires a well-designed transmission line to connect the thermoacoustic engine and the load or good phase shifter to improve the performance of the pulse tube cryocoolers (PTC). The transmission line or the phase shifter are commonly composed of a long slim tube, which has been investigated by researchers in the fields of PTCs and thermoacoustic systems. In 2005, an “acoustical pump” [2] was proposed by Luo et al. to increase the pressure ratio from 1.25 to 1.47. A cascade acoustic amplifier [3] was also proposed by the present authors to further increase the output pressure ratio of acoustic amplifiers and significantly reduce power consumption. A Helmholtz resonator [4] was then studied by Sun to focus acoustic power in a TE. In addition, as good phase shifters, inertance tubes are widely used in high frequency PTCs [5,6], theoretical and experimental research has been conducted to predict their characteristics [6–9].

[☆] This paper is modified from the original paper which is presented in Heat Powered Cycles Conference 2009, Berlin.

* Corresponding author. Tel./fax: +86 571 87952793.

E-mail address: limin.qiu@zju.edu.cn (L. Qiu).

As tools to control steady, simple harmonic sound field that have tonal, narrow band spectrums [10,11], Helmholtz resonators have been exploited to enhance or attenuate sound fields since ancient Greece [11,12]. They are widely used as mufflers in pipes and engines [13,14] to reduce noise and vibration. And the Helmholtz resonator in our previous study [4] was used as a transmission line to enhance acoustic wave, which amplifies the pressure amplitude from 0.20 MPa (p_{in}) to 0.32 MPa (p_{out}), $p_{out}/p_{in} = 1.60$. Then another type of Helmholtz resonator composed of a long open tube, a reservoir and a long close-end tube (see Fig. 1) was studied by us, which has larger amplifying ability [15] ($p_{in} = 0.14$ MPa, $p_{out} = 0.45$ MPa, $p_{out}/p_{in} = 3.21$). In these two Helmholtz resonators, the inertance of the long tube is mainly responsible for the pressure amplitude enhancement.

However, the impact of a Helmholtz resonator on the onset process of a TE has not been well understood. Onset indicates the transition of TEs from the stationary to periodic oscillating state when the heating temperature is larger than the critical value (the so-called onset temperature). As onset temperature determines the grade of the heat that a TE can utilize, the onset mechanism has been attracting more and more academic attention. The temperature distribution of the regenerator by thermocouples is commonly characterized to analyze the onset mechanism in experimental researches. The distribution by this traditional way is not complete because the numbers of the thermocouples is always limited.

In order to get the full-scale temperature distribution of the regenerator, infrared (IR) imaging is firstly used as a visualization method to characterize the onset mechanism in TE study. An IR

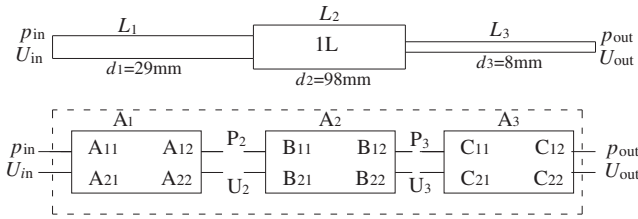


Fig. 1. Schematic diagram of Helmholtz resonator.

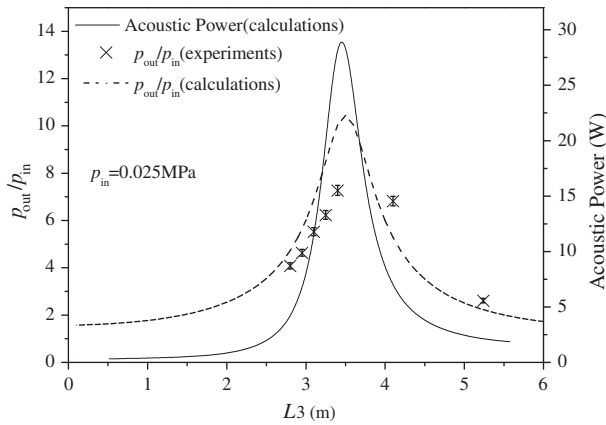


Fig. 2. The values of p_{out}/p_{in} and input acoustic power dependence on L_3 .

camera is used to measure the temperature distribution of the regenerator when the TE connects to the Helmholtz resonators with long tubes shown in Fig. 1. The transmission characteristics of the Helmholtz resonator are calculated to further explain the experimental phenomena.

2. Theoretical analysis

The method to simulate the transmission characteristics of the Helmholtz resonator with long tubes in thermoacoustic systems is detailed in our previous paper [16]. For a system coupling some ducts, the relations between the output pressure (p_{out}), volume flow rate (U_{out}) and inlet pressure (p_{in}), volume flow rate (U_{in}) can be expressed as:

$$\begin{bmatrix} p_{out} \\ U_{out} \end{bmatrix} = \mathbf{A}_n \mathbf{A}_{n-1} \cdots \mathbf{A}_2 \mathbf{A}_1 \begin{bmatrix} p_{in} \\ U_{in} \end{bmatrix} \quad (1)$$

where $\mathbf{A}_1, \mathbf{A}_2, \mathbf{A}_3, \dots$, or $\mathbf{A}_n$ is the transmission matrix of each individual duct. Once the transmission matrix is obtained, assume that by

knowing any two of the variables p_{out} , U_{out} , p_{in} , and U_{in} , the other two can be calculated. The transmission characteristics of the system can be described using the transmission matrix:

$$\mathbf{A}_n = \begin{bmatrix} \text{ch}(\sqrt{Z_n Y_n L_n}) & -\sqrt{Z_n/Y_n} \text{sh}(\sqrt{Z_n Y_n L_n}) \\ -\frac{1}{\sqrt{Z_n/Y_n}} \text{sh}(\sqrt{Z_n Y_n L_n}) & \text{ch}(\sqrt{Z_n Y_n L_n}) \end{bmatrix} \quad (2)$$

where

$$\begin{cases} Z_n = \frac{i\omega\rho_m}{A(1-f_v)} \\ Y_n = \frac{i\omega A}{\rho_m a^2} \left(\frac{1+(\gamma-1)f_k}{1+\varepsilon_s} \right) \end{cases} \quad (3)$$

where Z_n is the series impedance per unit length, Y_n is the shunt admittance per unit length, L_n is the length of each tube, ω is the angular frequency, ρ_m is the mean density of the working gas, A is the cross-sectional area of each tube, a is sound speed, γ is ratio of isobaric to isochoric specific heats, f_v and f_k are viscous function and thermal function, ε_s is boundary-layer approximation, and $i = \sqrt{-1}$.

For the Helmholtz resonator shown in Fig. 1, the transmission characteristics of the Helmholtz resonator can be obtained according to Eqs. (1)–(3). It should be noted that these equations are only applicable for laminar flow. However, the flow mentioned in this paper is turbulent. For turbulent flow, a turbulence correction should be made. So far, corrections for turbulence in an oscillating flow is not a mature science; there are only vague ideas for the corrections to turbulence. We proposed to make further corrections for turbulence when R/δ_v (R is the radius of the duct and δ_v is the viscous penetration depth of the gas) is large by increasing the viscous and thermal penetration depth, introducing a factor n , which is detailed in our paper [16].

In the simulations, the working gas of nitrogen is used with pressure of 2.2 MPa and frequency of 23 Hz. The diameters of tube L_1 and L_3 are 29 mm and 8 mm. The length of L_1 is 1.08 m. The volume of reservoir L_2 is 1 L, which can be considered as a short tube with an inner diameter of 99 mm and a length of 130 mm. The dimensions of L_1 and L_2 are fixed and the length of L_3 changed. U_{out} is 0 as the end of L_3 is blocked. Fig. 2 shows that the results of p_{out}/p_{in} and acoustic power are dependent on the length of L_3 when the inlet pressure amplitude is 0.025 MPa. The value of p_{out}/p_{in} increases with L_3 to the maximum, then decreases gradually. The length of L_3 corresponding to the peak value of p_{out}/p_{in} is called resonance length, which is 3.5 m. The calculation results indicate that the resonator absorbs the largest acoustic power at the resonance length. The calculation results agree well with the experiments (see the points in Fig. 2) under the same condition. The resonance length by the calculations is a little shorter than that by experiments, so the calculation results are always higher than the

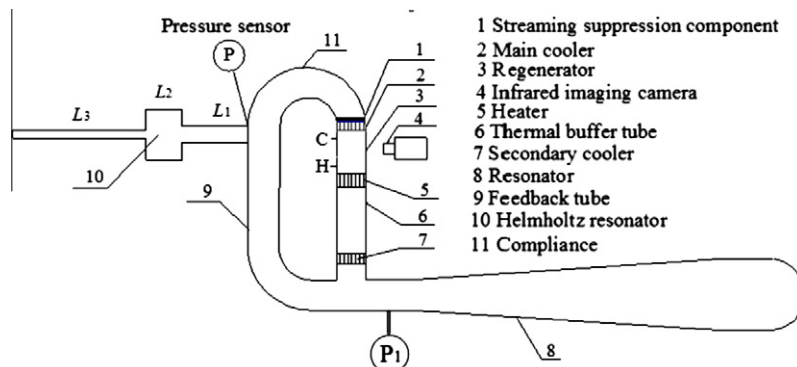


Fig. 3. Schematic diagram of the traveling-wave TE with an infrared imaging camera. Thermocouples are located at Positions H and C, pressure sensor is located at Compliance (Position P).

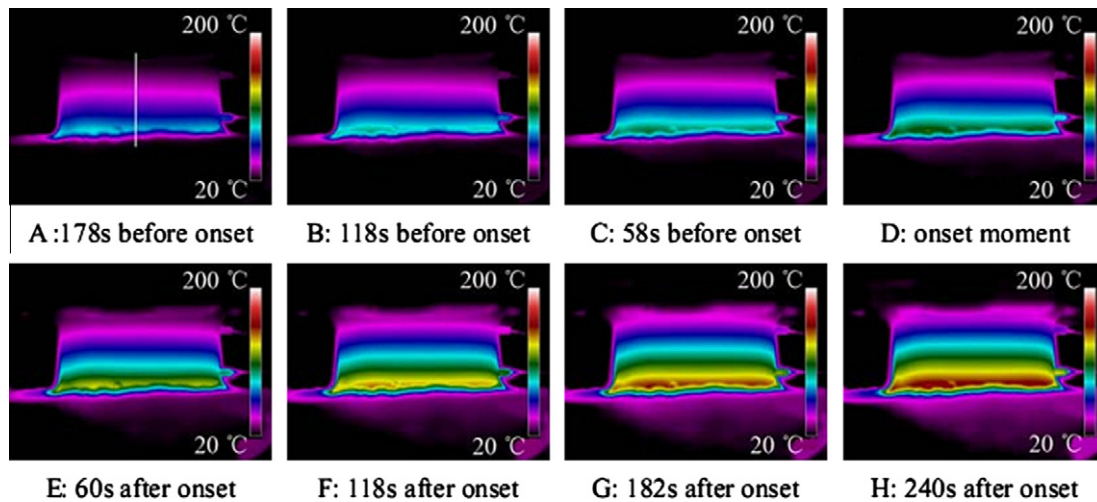


Fig. 4. IR images of the regenerator in the onset process.

experimental data before the peak value, but lower than the experimental data after the peak value.

3. Experimental results

A traveling-wave TE is the TE in which the sound wave is traveling. It has much higher potential efficiency than the standing-wave TE (the other kind of TE). Fig. 3 shows the schematic diagram of the traveling-wave TE with an infrared imaging camera. The traveling-wave TE is detailed in the literature [17], which consists of a loop and a resonator tube. The loop is the main part converting thermal energy to the acoustic power, consisting of heater, cooler, regenerator, and phase adjusters such as the feedback tube and compliance. The pressure data acquisition system is used in the experiments, which consists of pressure sensors (linear silicon piezoelectric type, KPY 46R), a data acquisition clip (NIPC-1200, 12 bit precision and a sampling frequency of 10 kHz), a computer, and a self-developed program for LabView 7.1 by National Instruments, Inc. The comprehensive error of the average pressure measurement is $\pm 2.22\text{E}-02$ MPa and that of the pressure amplitude measurement is $\pm 6.43\text{E}-04$ MPa.

Heating power is adjusted by changing the charging voltage to the heaters, and is displayed by a digital dynamometer. With a heating power of 1000 W, the uncertainty of the heating power measurement is ± 11.5 W.

An infrared imaging camera made by FLIR SYSTEMS is used to measure the temperature distribution of the regenerator. Visual images of the radiated heat of the objects can be obtained using the IR thermal imaging camera in the absence of light, thus the visual temperature distribution can be measured. IR imaging method may be weak in measurement accuracy when parameters are not set appropriately, thus temperature by thermocouples is measured to compare with that by IR imaging. A K-type thermocouple is used to measure the heater temperature, and two thermocouples are also used to measure the temperature near the hot and cold end of the regenerator (labeled as Position H and Position C, shown in Fig. 3).

The Helmholtz resonators with different L_3 were connected to the TE (with nitrogen as a working gas, where the pressure is 2.2 MPa) and the temperature distribution of the regenerator was measured visually by an IR camera. The Helmholtz with $L_3 = 5.7$ m is chosen to illustrate the onset process. Fig. 4 shows the temperature distribution evolution of the regenerator in the onset process. K-sheathed thermocouples placed at Position C

and Position H appear at the right side of each image. Using software ThermaCAM QuickReport 1.1, the temperature range and color of the images can be changed, and the temperature at any position of an image can be obtained. The display temperature of all the images in Fig. 4 is adjusted in the range of 20–200 °C, where the black region represents the lowest temperature, and the white shows the highest. Fig. 4D is the image at onset moment, while the images 3 min before (Fig. 4A–C) and 4 min after (Fig. 4E–H) the onset moment are also shown. All the images display obvious color separation in the axial direction of the regenerator, indicating the existence of a temperature gradient along the regenerator, while the same color in the horizontal direction indicates the same temperature. With a constant heating power of 1000 W, the temperature of the regenerator gradually increases. The TE onsets when the heater temperature reaches 168.1 °C, then the temperature of

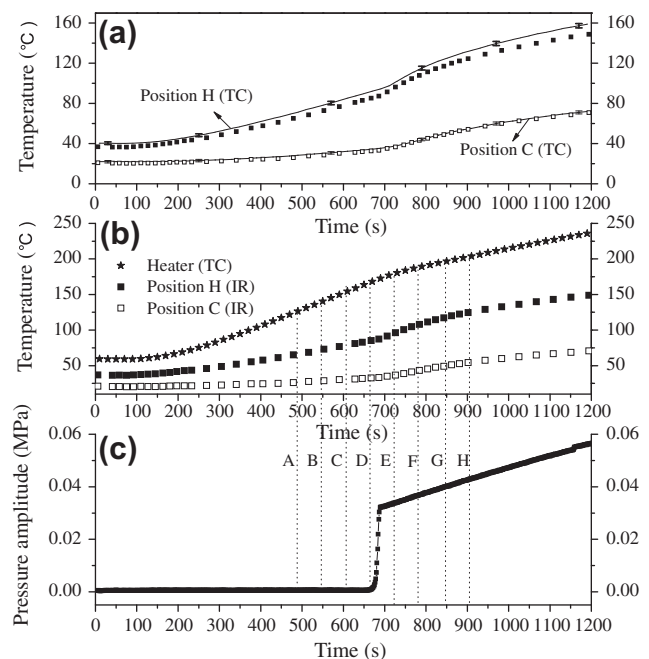


Fig. 5. Temperature and pressure amplitude evolution in the onset process: (a) temperature comparison between thermocouples (TC) and the infrared camera (IR); (b) temperature evolution of the heater and regenerator; (c) pressure amplitude evolution at compliance.

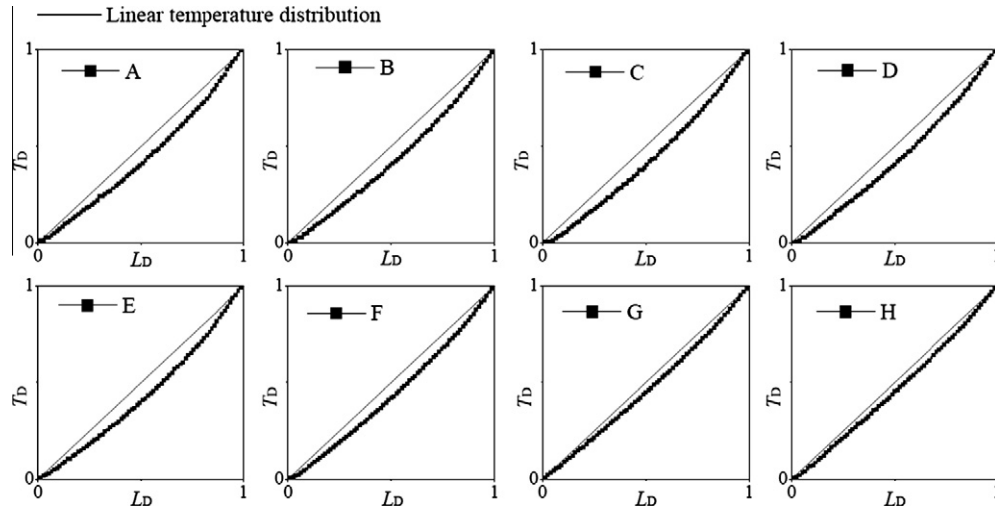


Fig. 6. The axial temperature distribution in the regenerator in onset process.

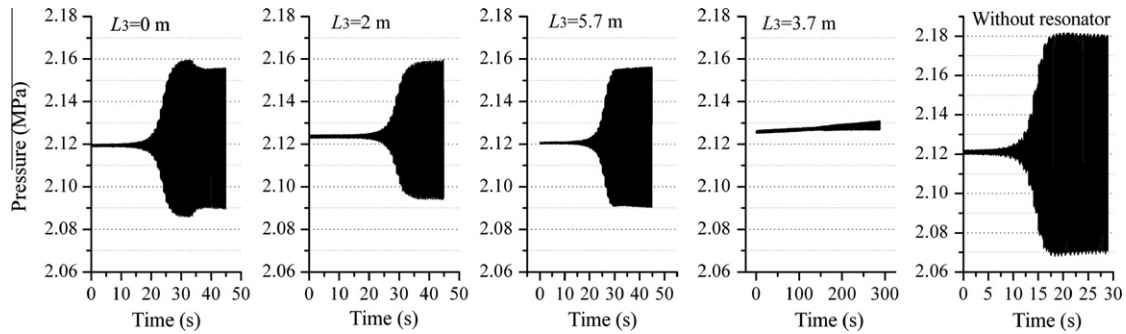


Fig. 7. The waveforms under different conditions.

the regenerator continues to rise because of the non-stop heating power.

Fig. 5 shows the dependence of simultaneous acquisition of pressure and temperature on time, where 0 s indicates the moment when the heater starts heating the TE. The time of A, B, ..., H in Fig. 5 is consistent with that in Fig. 4. The temperature results are given in Fig. 5a (TC represents the thermocouples). The temperature data in the IR images at Position C and Position H are also collected and compared with the data by the thermocouples. At Position C, the results by the two methods coincide well. At position H, they are close with a small deviation, especially at a higher temperature, as the temperature uncertainty of the thermocouples

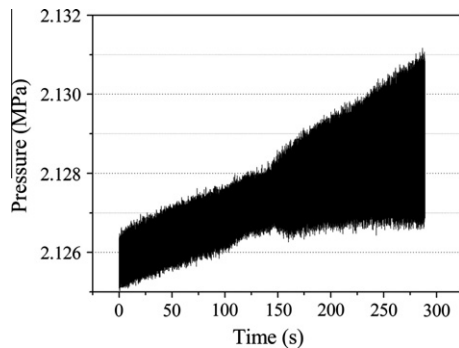


Fig. 8. Onset waveform when $L_3 = 3.7$ m.

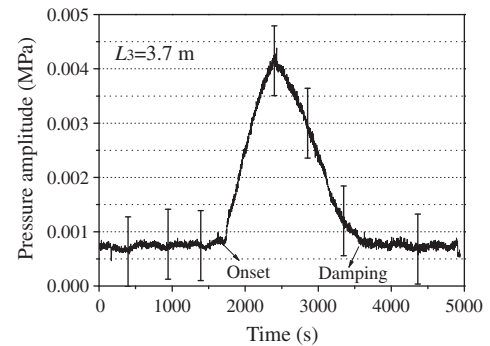


Fig. 9. The variation of pressure amplitude when $L_3 = 3.7$ m.

increases with temperature. The results shows that measurement accuracy by IR imaging is acceptable. Fig. 5b and c gives the temperature and pressure evolution during the onset process. Before onset (A, B, and C) the temperature of the heater and regenerator gradually increases. Meanwhile the temperature difference between the hot and cold end of the regenerator rises, reaching the critical value at the time of onset (D), where onset begins.

The temperature distributions of the regenerator along the axial direction are collected (see the white line Fig. 4A) and displayed in Fig. 6 with the non-dimensional length L_D as the horizontal axis and non-dimensional temperature T_b as the longitudinal axis. The definition is $L_D = L/\Delta L$, where L is the distance away from the

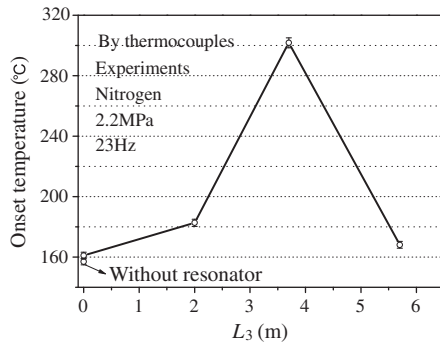


Fig. 10. The onset temperatures with different length of L_3 .

cold end of the regenerator and ΔL is the whole length of the regenerator; $T_D = (T - T_0)/(T_H - T_0)$, where T , T_H , and T_0 represent the regenerator temperature at the position of L , hot end and cold end. The temperature distribution of the regenerator is nonlinear before onset (Fig. 6A–C). This nonlinear distribution is mainly influenced by the large thermal resistance in the axial direction between the stainless screens in the regenerator and large heat leakage in the radial direction (in the radial direction thermal conduction of the stainless screen is good enough, in addition, the outside wall of the regenerator is not insulated). When the temperature difference between the hot and cold end of the regenerator reaches the critical value, the working gas starts to oscillate. In a traveling-wave TE the penetration depth of the gas is much larger than the characteristic dimension of the stainless screen, the sufficient heat transfer between them leads to the change of the temperature distribution after onset (see Fig. 6E–H), the temperature distribution line goes closer and closer to the linear line.

The waveforms at different length of L_3 are compared in Fig. 7, meanwhile the waveform when TE onset occurs without the Helmholtz resonator is also shown. The display range of the pressure ratio is adjusted the same to represent the obvious difference under different conditions. The Helmholtz resonator decreases the pressure amplitude of the TE when it onsets. The pressure amplitude jumps to the largest value without the Helmholtz resonator. As above mentioned analysis in Fig. 2, when the Helmholtz resonator is connected to a TE, the value of the pressure amplitude at the onset moment depends on the acoustic power consumption by the resonator. The pressure amplitude has the largest value when

$L_3 = 0$, as it needs the smallest acoustic power. After the TE onsets, the pressure amplitude decreases to a constant immediately after it jumps to the peak value because of the existence of the Helmholtz resonator. The onset waveforms are nearly the same when $L_3 = 2$ m and $L_3 = 5.7$ m, as the acoustic power consumptions of these are very close; both are larger than that when $L_3 = 0$. The pressure amplitude comes to the smallest value (near 0 MPa) when $L_3 = 3.7$ m, as the TE onset near the resonance length of L_3 , the resonator absorbs the largest acoustic power. The detail is represented in Fig. 8.

When L_3 is close to the resonance length, Fig. 8 indicates that the pressure amplitude increases smoothly without a jump. No obvious onset waveform can be distinguished in a longer duration of 300 s. This duration includes onset process which lasts about 25 s. After onset, the pressure amplitude increases with the heating temperature, thus no steady state is observed. In Fig. 9, the smooth change of pressure amplitude also appears in the whole process, including both onset and damping, which differs from the sharp increase under the other conditions when L_3 is far from the resonance length (for example, an obvious jump occurs in Fig. 5c when the TE onsets). In the onset mechanism study, this phenomenon that a TE onsets without a pressure amplitude jump has not been observed before in the literature.

The onset temperature T_H (the heater temperature at the onset moment, measured by thermocouples) changes with the length of L_3 , see Figs. 10 and 11. The Helmholtz resonator increases the onset temperature of the TE. Without the resonator, T_H is the lowest. With the resonators, T_H changes with the length of L_3 and its value is related to the acoustic power consumption. The onset temperature increases in turn when $L_3 = 0$ m, $L_3 = 5.7$ m, $L_3 = 2$ m, and $L_3 = 3.7$ m. The reasons are similar with the above-mentioned discussion of acoustic power consumption. T_H is the largest when $L_3 = 3.7$ m, as the resonator absorbs the largest acoustic power from the TE, which delays the onset process of the TE.

The IR images of the regenerator at the onset moment also show the obvious differences when the length of L_3 changes, as Fig. 11. The resonator near the resonance length has the largest effect on the performance of the TE.

The Helmholtz resonator with long tubes has two functions: the first is to reduce the pressure amplitude of the TE, the second is to amplify the pressure amplitude within the resonator along its length. The first has negative and the second has positive effect on the pressure amplification effect, thus the pressure amplitude at the end of the resonator is a compromise of these two functions.

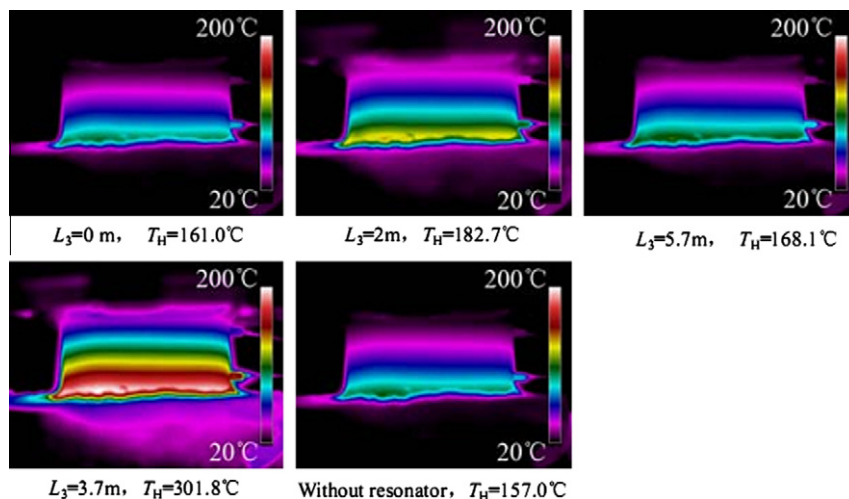


Fig. 11. IR images of the onset moment with different L_3 .

When vibration caused by thermoacoustic effect is not wanted, resonators should work at resonance length; In contrast, when amplification of pressure amplitude is preferred, resonator should work away from the resonance length.

4. Conclusion

Using an infrared imaging camera as a means of characterizing temperature distributions of thermoacoustic regenerators, the visual IR images have been obtained for the first time in a TE. The new method can reveal the full-scale temperature distribution of the regenerator that the traditional method by thermocouples cannot. As the verification basis for the simulation, especially for a Computational Fluid Dynamics (CFD) study, this study supplies sufficient experimental data showing that the infrared imaging may be used as a powerful method in the TE study.

The impacts of the Helmholtz resonator on the onset process of a TE are studied theoretically and experimentally. The resonator reduces the pressure amplitude at the onset moment, which depends on the acoustic power absorbed from the TE. The amplitude jumps to the largest value without the Helmholtz resonator. Meanwhile, the Helmholtz resonator increases the onset temperature of the TE, which also depends on the acoustic power absorption. Onset without a sudden increase of pressure amplitude is firstly observed in the TE study when the Helmholtz resonator is at its resonance length.

Acknowledgments

The project is supported by China National Funds for Distinguished Young Scientists under Contract No. 50825601 and partly by the Major State Basic Research Development Program of China under Contract No. 2010CB227303. We thank Dr. Laura Grossenbacher from University of Wisconsin–Madison for the correction in English writing.

References

- [1] Backhaus S, Swift GW. A thermoacoustic stirling heat engine. *Nature* 1999;399:335–8.
- [2] Luo EC, Hu JY, Dai W, et al. An acoustical pump capable of significantly increasing pressure ratio of thermoacoustic heat engines. *Chin Sci Bull* 2006;51:1014–6.
- [3] Sun DM, Qiu LM, Wang B, et al. Transmission characteristics of acoustic amplifier in thermoacoustic engine. *Energy Convers Manage* 2008;49:913–8.
- [4] Sun DM, Qiu LM, Wang B, et al. Novel Helmholtz resonator used to focus acoustic energy of thermoacoustic engine. *Appl Therm Eng* 2009;29:945–9.
- [5] Kanao K, Watanabe N, Kanazawa K. A miniature pulse tube refrigerator for the temperature below 100 K. *Cryogenics* 1994. IEC Suppl.) 167–70.
- [6] Godshalk K, Jin C, Kwong Y, et al. Characterization of 350 Hz thermoacoustic driven orifice pulse tube refrigerator with measurements of the phase of the mass flow and pressure. *Adv Cry Eng* 1996;1411–8.
- [7] Luo EC, Radebaugh R, Lewis M. Inertance tube models and their experimental verification. *Adv Cry Eng* 2004;49:1485–92.
- [8] Dai W, Hu JY, Luo EC. Comparison of two different ways of using inertance tube in a pulse tube cooler. *Cryogenics* 2006;46:273–7.
- [9] Schunk L, Nellis G, Pfothner J. Experimental investigation and modeling of inertance tubes. *J Fluid Eng* 2005;1029–37.
- [10] De Bedout JM. Adaptive–passive noise control with self-tuning Helmholtz resonators. Purdue University: West Lafayette; 1996.
- [11] De Bedout JM, Franchek MA, Bernhard RJ, et al. Adaptive–passive noise control with self-tuning Helmholtz resonators. *J Sound Vib* 1997;202:109–23.
- [12] Ingard U. Notes on sound absorption technology Poughkeepsie. NY: Noise Control Foundation; 1994.
- [13] Munjal ML. Acoustics of ducts and mufflers with application to exhaust and ventilation system design. New York: John Wiley; 1987.
- [14] Selamet A, Kothamasu V, Novak JM. Insertion loss of a Helmholtz resonator in the intake system of internal combustion engines: an experimental and computational investigation. *Appl Acoust* 2001;62:381–409.
- [15] Bai K, Qiu LM, Wang B, et al. Transmission characteristics of coupled pipe system in thermoacoustic engine. *J Zhejiang Univ* 2009;43:1463–8.
- [16] Wang B, Qiu LM, Sun DM, et al. A passive network model for large diameter thermoacoustic tube systems and its experimental verification. *Appl Acoust* 2010;71:922–30.
- [17] Sun DM, Qiu LM, Zhang W, et al. Investigation on traveling wave thermoacoustic heat engine with high pressure amplitude. *Energy Convers Manage* 2005;46:281–91.